

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

In re Patent Application of:      Brett Masters, et al.  
Serial No.:                              10/826,952  
Filed:                                      April 15, 2004  
Entitled:                                  VIBRATION BASED POWER  
    GENERATOR  
Group Art Unit:                        2834  
Examiner:                                J. Waks

**DECLARATION OF PRIOR INVENTION  
UNDER RULE 131**

Commissioner for Patents  
P.O. Box 1450  
Alexandria, VA 22313-1450

This declaration is to establish completion of the invention in the above-identified patent application in the United States, at a date prior to January 14, 2004, the earliest effective filing date of United States Published Application No. 2006/0064972 (Allen). This declaration is submitted accompanying a response to the Office Action dated August 28, 2006.

The persons making this declaration are the applicants, Brett Masters, Brooks Radighieri, Marcel Huigsloot, Gert Muller, Andries Du Plessis, Marthinus van Schoor, Matt Schaefer and Chris Ludlow.

To establish the date of completion of the invention of this application and diligence in reducing the invention to practice, the following attached exhibits are submitted as evidence:

Exhibit A - A copy of a provisional patent application entitled "Subterranean Well Lock-In Power Generation System," filed on July 11, 2002.

Exhibit B - A copy of a letter between a patent attorney and the assignee of the present application, transmitting a draft of the application.

Additionally, the undersigned applicants hereby declare that:

1. We conceived the invention of the present application prior to the Allen patent application filing date;
2. As shown by the attached Exhibit A, we possessed a complete understanding of the invention, including the manner of making and using the invention, prior to the Allen patent application filing date;
3. Diligence was exercised in preparing and filing the present application from a time at least prior to the Allen patent application filing date and until filing of the present patent application on April 15, 2004;

PATENT

Attorney Docket No.: 2003-IP-009957 U1 USA

4. As shown by the attached Exhibit B, dated October 29, 2003, preparation of the present patent application was in process, and due diligence was being exercised in preparing and filing the present patent application, prior to the Allen patent application filing date.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

  
BRETT MASTERSDated: 11/20/06\_\_\_\_\_  
BROOKS RADIGHIERI

Dated: \_\_\_\_\_

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MARCEL HUIGSLOOT

Dated: \_\_\_\_\_

PATENT

Attorney Docket No.: 2003-IP-009957 U1 USA

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BRETT MASTERS

Dated: \_\_\_\_\_

  
BROOKS RADIGHIERIDated: 11/16/2006

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MARCEL HUIGSLOOT

Dated: \_\_\_\_\_

PATENT

Attorney Docket No.: 2003-IP-009957 U1 USA

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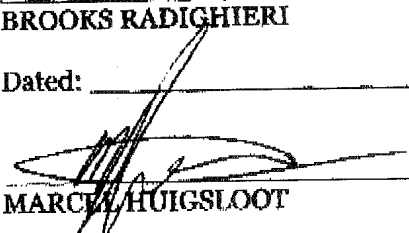
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**PATENT**

**Attorney Docket No.: 2003-IP-009957 U1 USA**

  
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**GERT MULLER**

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**ANDRIES DU PLESSIS**

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**MARTHINUS VAN SCHOOR**

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**MATT SCHAEFER**

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**CHRIS LUDLOW**

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Attorney Docket No.: 2003-IP-009957 U1 USA

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ANDRIES DU PLESSIS

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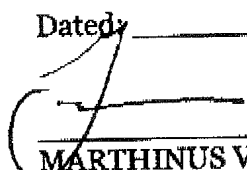
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CHRIS LUDLOW

Dated: 11/16/2006

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MARTINUS VAN SCHOOR

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\_\_\_\_\_  
MATT SCHAEFFER

Dated: 20 NOVEMBER 2006

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CHRIS LUDLOW

Dated: \_\_\_\_\_

## **EXHIBIT A**

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Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

PTO/SB/16 (8-00)  
Approved for use through 10/31/2002. OMB 0851-0032  
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

# PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

INVENTOR(S)					
Given Name (first and middle (if any))		Family Name or Surname		Residence (City and either State or Foreign Country)	
Brett Gert Andres Marthinus		Masters Muller Du Plessis van Schoor		Belmont, MA Norwood, MA Arlington, MA Medford, MA	
<input checked="" type="checkbox"/> Additional inventors are being named on the <u>1</u> separately numbered sheets attached hereto					
TITLE OF THE INVENTION (280 characters max) SUBTERRANEAN WELL LOCK-IN POWER GENERATION SYSTEM					
Direct all correspondence to: CORRESPONDENCE ADDRESS					
<input type="checkbox"/> Customer Number		<input type="text"/>		<div>Place Customer Number Bar Code Label here</div>	
OR Type Customer Number here					
<input checked="" type="checkbox"/> Firm or Individual Name		Jason D. Shanske			
Address		Iandiorio & Teska			
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City		Waltham		State	MA
Country		USA		ZIP	02451-1018
		Telephone	781-890-5678	Fax	781-890-1150
ENCLOSED APPLICATION PARTS (check all that apply)					
<input checked="" type="checkbox"/>	Specification	Number of Pages	<input type="text" value="17"/>	<input type="checkbox"/>	CD(s), Number
<input checked="" type="checkbox"/>	Drawing(s)	Number of Sheets	<input type="text" value="18"/>	<input type="checkbox"/>	Other (specify)
<input type="checkbox"/>	Application Data Sheet. See 37 CFR 1.76				
METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT (check one)					
<input checked="" type="checkbox"/>	Applicant claims small entity status. See 37 CFR 1.27.				FILING FEE AMOUNT (\$)
<input checked="" type="checkbox"/>	A check or money order is enclosed to cover the filing fees				
<input checked="" type="checkbox"/>	The Commissioner is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number				
<input type="checkbox"/>	Payment by credit card. Form PTO-2038 is attached.				
The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.					
<input checked="" type="checkbox"/>	No.				
<input type="checkbox"/>	Yes, the name of the U.S. Government agency and the Government contract number are:				

Respectfully submitted,

SIGNATURE

TYPED or PRINTED NAME Jason D. Shanske

TELEPHONE 781-890-5678

Date

7/11/02

REGISTRATION NO.

43,915

(if appropriate)

Docket Number:

MIDE-103J

## USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

This collection of information is required by 37 CFR 1.51. The information is used by the public to file (and by the PTO to process) a provisional application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 8 hours to complete, including gathering, preparing, and submitting the complete provisional application to the PTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, D.C. 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Box Provisional Application, Assistant Commissioner for Patents, Washington, D.C.

# PROVISIONAL APPLICATION COVER SHEET

## Additional Page

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Docket Number	MIDE-103J	Type a plus sign (+) inside this box →	+
INVENTOR(S)/APPLICANT(S)			
Given Name (first and middle (if any))	Family or Surname	Residence (City and either State or Foreign Country)	
Matt Chris	Schaefer Ludlow	Burlington, MA Boston, MA	

Number 2 of 2

**WARNING:** Information on this form may become public. Credit card information should not be included on this form. Provide credit card information and authorization on PTO-2038.

**Invention Disclosure – 16<sup>th</sup> June, 2002****(a) Subterranean Well Lock-In Power Generation System**

Author of the Disclosure: Dr. Brett Masters, Mide Technology Corporation

**Inventors:**

Brett Masters, 84 Fairview Ave, Belmont MA  
Gert Muller, 382 Walpole Street, Norwood MA  
Andres Du Plessis, 9 Everett Street, Arlington MA  
Marthinus van Schoor, 52 Marion Street, Medford MA  
Matt Schaefer, 26 Beacon Street, Burlington MA  
Chris Ludlow, 18 Andersen St, Boston, MA

**Assignee:**

Halliburton Energy Services – Subterranean Well Applications  
Midé Technology Corporation - other

**(b) Background & Cross-references (Patents & Disclosed Art in the Area)**

Production of electrical power from down-hole vibrations or flow is necessary to service a variety of current and future applications. Reliable power sources that enable regulated production and reliable safety systems are needed.

The advent of a steady, long life, power sources in the down-hole production environment will give rise to new devices and applications for intelligent control of new production scenarios.

Several patents exist as prior art that broadly claim the use of piezoelectrics in subterranean conduit, or production scenarios. Neither provide the means for efficiently achieving the goal for down hole production. This patent provides such an efficient means by coupling a levered piezoelectrics to a fluid lock-in device.

The Lock-in device may further be designed to generate power through magnetic means. The magnetic means being a soft magnet moving with respect to a coil of high turns ratio. The magnetic means and the pivoting arms being designed to be consistent with the lock-in frequencies.

***Prior Art Regarding Down-hole Piezoelectric Power Generators that are Flow Driven*****WO 02/10553 A1 Vibration Based Power Generator**

Vary broadly describes fluid flow through a conduit that causes a member to displace or vibrate. The displacement of the member is utilized to induce strain in a piezoelectric material, thereby causing the piezoelectric material to produce electricity. It quotes that "various means maybe used to create turbulence in the flow, thereby increasing the displacement of the member, resulting in increased power output from the generator.

Although many means are claimed, and in general, flow induced fluctuating strain energy is what is desired, none are effective at coupling the flow to fluctuating piezoelectric strain energy.

**US 6,011,346 Apparatus and Method for Generating Electricity from Energy in a Flowing Stream of Fluid**

Discloses a method and apparatus for extracting energy from fluid flowing in a pipe using piezoelectric elements. The patent discloses a piezoelectric member located stream wise in pipe flow and a flow restrictor, which causes flow to separate stream wise, generating a differential pressure that acts on the surface of the piezoelectric elements. This pressure differential leads to strain and eventual electrical response through the piezoelectric effect. The flow restrictor is

movable relative to the piezo member to change the direction of deformation of the element. In this instance the arrangement of piezo elements are acting as a flag does, flapping stream wise activated by restricted flow pressure differential.

### *Prior Art Regarding Piezoelectric Power Generators*

#### US 5,703,474 Power Transfer of Piezoelectric Generated Energy

This patent describes a technique for extracting energy from a dynamically stressed piezo element. The post-rectified piezo voltage is monitored for fluctuating peaks. At the sensed peak the power conduction path from the element to the energy storage device is enabled. This power conduction path includes inductive and capacitive elements to aid in extraction of charge from the element.

#### US 5,801,475 Piezo-Electricity Generation Device

The patent describes a technique by which to extract energy from a dynamically stressed piezo element. The method requires a rectifier, an accumulation device, a voltage setting means powered only by the piezo element, and a signal output means, powered only by the piezo element, for receiving all the electrical charge accumulated in the accumulator.

### *Prior Art Regarding Piezoelectric Mechanical Leveraging*

#### US 5,907,211 High Efficiency Large Stroke Electromechanical Actuator

This patent describes an actuator mechanism by which to lever small piezoelectric motions into large amplitude motions. Within reasonable tolerances the device can have a leverage factor as large as 15. It requires two pivoting frames and at least one longitudinal member that extends in response to electrical stimulus.

This mechanism is one possible embodiment of a piezo leveraging technique that we could use, in series with other mechanical levers, to leverage the induced lock-in buffeting body motion into piezoelectric material strain energy. In of itself it does not provide sufficient gain for our lock-in device.

#### US 4,769,569 Piezoelectric Stack Motor Stroke Amplifier

This patent describes an arrangement of piezo stack elements and a mechanical leveraging technique with which to obtain gained motion from the limited piezo electric motion. This mechanism is another possible embodiment of a piezo leveraging technique that we could use, in series with other mechanical levers, to leverage the induced lock-in buffeting body motion into piezoelectric material strain energy. In of itself it does not provide sufficient gain for our lock-in device.

#### US 4,808,874 Double Saggital Stroke Amplifier

This patent describes an arrangement of piezo stack elements and a mechanical leveraging technique with which to obtain gained motion from the limited piezo electric motion. This mechanism is another possible embodiment of a piezo leveraging technique that we could use, in series with other mechanical levers, to leverage the induced lock-in buffeting body motion into piezoelectric material strain energy. In of itself it does not provide sufficient gain for our lock-in device.

### *Pertinent other references:*

- 1) Blevins, Robert, *Flow-induced vibration*, Van Nostrand Reinhold Co., NY, 1977.
- 2) *Extracting Energy From Natural Flow*, NASA Tech. Briefs, Spring 1980, Vol. 5, No.1, MFS-23989.
- 3) Parkinson, Geoffrey, *Phenomena and Modelling if Flow-induced Vibrations of Bluff Bodies*, Progress in Aerospace Sciences, Vol.26, pp.169-224, 1989.
- 4) Jaffe, B.; Cook, W.R., Jr; Jaffe, H.. "Piezoelectric Ceramics," Marietta: R.A.N. Publishers; 1971.
- 5) Physik Instrumente web site, [www.physikinstrumente.com](http://www.physikinstrumente.com).
- 6) "Characteristics of Relaxor-Based Piezoelectric Single Crystals for Ultrasonic Transducers," *IEEE Trans. on Ultrasonics, Ferroelect. and Freq. Control*, 44(5):1140-1147 (September 1997)

**(c) Summary of the invention.**

The invention is a lock-in flow galloper that fluctuates at high frequency in fluid flow. When placed in flow a bluff body sheds vortices. When the bluff body is mounted by elastic means, and under certain flow conditions, these vortices lock-in, or dynamically interlace, in the wake of the bluff body causing the fluctuating lift forces. These forces and the body's elastic restraint forces interact in a manner that amplifies the side-to-side motion of the body. The motion either reaches maximum amplitude allowable due to elastic restraint, or flow force saturation, or both.

In one embodiment the fluctuating mechanical motion is efficiently levered down to relatively small, allowable, piezoelectric element motions. The piezoelectric element, in turn, converts the mechanical energy to available electrical energy. Maximizing the available electrical power results from efficient mechanical leveraging at elevated frequencies and judicious piezoelectric element usage, e.g. mechanically in series while electrically in parallel.

In another embodiment the fluctuating motion is efficiently coupled to a magnetic power generation means. This means is in the form of a permanent magnet ("soft" magnetic material) and a pickup coil that registers voltage and permits current flow when the magnetic field changes in its core. This device for producing power, unlike the piezoelectric element, capitalizes on the large amplitudes and rates produced by the lock-in dynamics. While the permanent magnets, or the coil, could be incorporated with the bluff body, this needlessly complicates design. In the disclosed embodiment the permanent magnets make a inertial lever with the bluff body, and the full bluff body motion is converted to relative magnet coil dynamic displacement.

In a further embodiment lock-in power production is achieved by coupling both levered piezoelectric means, as elastic supports, with magnet means, as a counter balanced inertia load. In this embodiment maximum power is achieved by extracting energy from the fluctuating strain energy witnessed by the piezoelectric elements and from the relative inertial motion witnessed by coil and magnet.

It is an object of all embodiments to provide a best means for achieving flow speed impinging on the bluff body while not obstructing or restricting the main core flow and thus not causing large pressure drop across the device. This enables device lock-in at the lowest possible net core flow speeds, or conversely raise the device output power by enabling a higher mechanical response frequency for the constants flow speeds. Both can be desirable features of the device design.

It is a further object of the levered piezo embodiment to best arrange piezoelectric elements in order to match the desired electrical output impedance and thus not compromise overall production efficiency by requiring the use of an electrical converter.

It is a further object of the lock-in levered piezo embodiment to mechanically couple the bluff body motion to the piezoelectric element motion/strain in an efficient manner while constrained to provide highest possible response frequency of the overall device at the lowest possible flows.

It is a further object of the lock-in magnetic embodiment to mechanically couple the bluff body motion to the magnetic element motion in an efficient manner while constrained to provide highest possible response frequency of the overall device at the lowest possible flows.

**(d) Brief description of the several views of the drawing, if there are drawings.**

Fig. 1 Shows prior art (Figure 1 from WO 02/10553 A1)

Fig. 2 Shows prior art (Figure 1 from 6,011,346)

Fig. 3 illustrates the Lock-In Power Generator – implementation of piezo element supported beam

Fig. 3b illustrates the systematic power production overview with piezo sources

Fig. 3c illustrates the Lock-In Power Generator – magnetic implementation of bluff body connection

Fig. 3d illustrates the Lock-In Power Generator – prototype magnetic implementation

Fig. 4 illustrates flow interaction with the bluff body

Fig. 5 is a plot showing the lock-in flow range

Fig. 6 illustrates typical forcing coefficients from Blevins (for air)

Fig. 7 illustrates Lock-in power generator pipe implementation (offset from main bore flow)

Fig. 8 illustrates the preferred mechanism for leveraging piezo elements

Fig. 9 prior art - another mechanism for leveraging piezo elements

Fig. 10 another mechanism for leveraging piezo elements

Fig. 11 illustrates flow diverter embodiments

Fig. 12 illustrates functional bluff body head shapes

### **(e) Detailed Description.**

The piezoelectric effect was discovered in the 1890's by Currie. The effect found no real applications drive until the second world war when over 30 million devices were constructed for communications purposes. These devices were small quartz transducers and resonators. Discovery of materials with higher piezoelectric constants in the past 30 years has led to development of devices that utilize the higher induced mechanical strains and work, or conversely induced fields in response to mechanical strains.

It was well described, and known in the art prior to 20 years ago, that electrical power was available from a mechanically driven piezoelectric element. It was also obvious that mechanical energy, in the form of fluctuating forces was available, in nearly every vibration (inertial or direct stress) or flow (time dependent pressures) environment. Prior art has broadly claimed that such mechanical energy exists in a subterranean well environment, as it does in most conduit flow scenarios, and that piezoelectric means should be able to extract energy from it. This is generally true, but no devices have been presented in the art to date that do this in an efficient manner. What remains is the development of a device that efficiently extracts power from such environment to make it a worthwhile pursuit.

This patent describes a device that efficiently extracts power from flow. The flow does not necessarily have to be turbulent, or have any pre-existing pressure gradients. The device when coupled to the flow results in dynamic mechanical motions. The motions are in turn coupled to dynamic stressing of piezoelectric elements where the power is extracted through the use of the piezoelectric effect, or coupled to permanent magnet motion, where power is extracted in accordance with Lenz's law relating change in potential to change in magnetic flux within a coil.

It is typically an object of a pipe flow scenario, be it subterranean or other, to provide a flow path with minimal pressure drop across it. Overall flow path pressure drop results in reduced flow capacity for a given source pressure, which is a disadvantageous feature. It is an object of this invention to provide an energy extraction mechanism with minimal pressure drop across the net flow section in which it is implemented, and thus, when combined with an effective coupling mechanism, provide the best efficiency of power extraction for a piezoelectric device.

Figure 3a through 3c shows the invention. Typically flow is expanded into a cross section that is larger than the desired transport conduit flow path. This flow impinges on an elastically supported bluff body. Induced body motion interacts with flow instability to result in what is known as lock-in motional response. The response is a coupled driven resonance and maybe described by a limit cycle oscillator.

The dynamic motion is leveraged onto piezoelectric elements, be it either through flexible means, where the piezoelectric elements provide part of the flexibility, or substantially rigid means, where the piezoelectric elements provide the majority of the flexibility. In either case the mechanical resonance frequency of the body is designed to be commensurate with the flow instability frequency for a range of flows.

The dynamic mechanical energy, or available mechanical power, of the piezoelectric elements are converted to electrical power through rectifying, or some such, means with piezoelectric elements connected in series, or parallel, to best couple to the electrical load. That is, the piezoelectric elements may be mechanically in series but electrically in parallel to maximize the current producing capacity, thus lower the output voltage, providing maximal power for a given electrical load.

Figures 3d and 3e show how permanent magnets may be used in a pivot arm design. In this design the flexure provides the elastic means for the mechanical resonance, but this may also be provided by leveraged piezos. The permanent magnets are placed in a position where the inertial amplitude of the motion is maximized, for reasonable life cycle strains in the elastic support. The magnets contribute to the inertia about the pivot flexure and therefore the flexure, considering the inertia, is designed to give a mechanical device resonance at the lock-in wake frequency range consistent with the flow range in the conduit.

## Lock-In Flow Phenomenon

It has been known since the 1970's [Hartlen-Currie] that under certain circumstances flow can induce dynamic response in an elastically mounted body. Above a critical value of local flow speed, steady flow around a body becomes unstable and a periodic flow regime arises. In this case vortices are shed periodically downstream. This is known as von Karman vortex shedding.

The lock-in phenomenon is when the obstructing bodies lateral dynamic motion controls the vortex shedding frequency. Figure 4 shows this schematically for a square cross section body. Lock-in occurs in the resonance regime where the body's mechanical resonance frequency is close to the vortex shedding frequency.

Vortices shed from both sides of the body interlace stream-wise in the wake resulting in a harmonically varying lift force. The elastic forces on the body, couple with the inertial and the lift forces to result in resonant like motion that grows in amplitude with flow rate in order to achieve some balance.

Figure 5 shows a plot of the non-dimensional wake frequency as a function of flow. The wake frequency,  $f$ , is a function of the Strouhal number,  $St$ , where

$$St \equiv \frac{fD}{U} \approx 0.2$$

for,

$$10^2 \leq Re \leq 10^5, \quad Re = \frac{UD}{\nu}$$

where  $U$  is the local impinging stream velocity,  $D$  is the characteristic dimension of the body,  $\nu$  is the kinematic viscosity, and  $Re$  is the Reynolds number. When the flow velocity reaches a certain critical value, that at which the wake frequency is commensurate with the mechanical resonance frequency, the wake frequency "locks in" with the mechanical frequency for a range of flows. Above these flows the wake frequency returns to the lineal relationship with slope described by the Strouhal number.

For our implementation we have Reynolds numbers in the range 10,000 to 50,000. To give an example consistent with the sizing of a down hole production scenario, a characteristic dimension of 2 cm in 1 m/sec flow gives a wake frequency of 10 Hz for a Strouhal number equal to 0.2.

The lock in phenomenon can be mathematically represented by the equations of motion for a single degree of freedom oscillator driven by a force consisting of a series of empirically derived coefficients that are position rate dependent.

$$m \ddot{q} + 2\zeta\omega_n \dot{q} + \omega_n^2 q = \frac{1}{2} \rho U^2 D \sum_{i=1}^N a_i k_i \left( \frac{\dot{q}}{U} \right)^i$$

$$C_y = \sum_{i=1}^N a_i \left( \frac{\dot{q}}{U} \right)^i$$

Figure 6 shows lift coefficient plots [Blevins] for a couple of different body cross section shapes driven in air flow. In practice the coefficients curve fit to these curves and are only valid for certain body shapes and flow conditions. But, from the equation, and the plot, one can see that under certain conditions the flow forces interact with the oscillator to generate amplified motion.

Figures 7 shows the preferred embodiment to date. The bluff body head is mounted so as to be substantially non intrusive into the conduit internal diameter. A cutaway section shows how this is accomplished in Figure 7. The head resides in an adjacent keyway shaped so as to expand flow from the main bore toward and around the head. A preferred head shape is shown where wake vortices are shed from the edges and the resulting fluctuating pressure force reacted by the trailing shaped body. A pivoting arm attaches the head to pivot blade flexures. The blade flexures allow rotation of the head and arm from side to side of the flow cutaway. Stoppers that limit the motion maybe added. The blade flexures couple the turning motion, at the pivot, to motion, essentially in the longitudinal direction, of the levered piezo element mechanisms (one on either side of the pivot arm). The lever mechanisms turn the longitudinal into forces that dynamically strain the piezo elements.

It is an advantageous feature to produce power for conduit flows as low as possible while not causing undesirable pressure drop across the implemented section of conduit. To achieve this the bluff body head is mounted so as to be substantially non intrusive into the internal conduit diameter. Figure 7d shows an end view without surrounding pipe structure.

As shown in Figure 7d the head is approximately 0.7 inches in dimension across the bluff face and is approximately 1.25 inches in height. The conduit internal diameter is approximately 2.9 inches. The head resides in an adjacent keyway approximately 2 inches in width leaving room for lateral peak displacements on the order of approximately 0.7 inches.

In the preferred embodiment flow is achieved in the keyway by use of a shaped expansion ramp from the conduit internal diameter to an allowable outer diameter. The ramp is placed upstream of the head directing flow into the keyway where the head substantially resides. Prior to the head a local flow restrictor is placed as shown in Figure 7e. The flow restrictor resides substantially within the keyway. It serves to locally increase the flow speed and provide a local flow angle with respect to the head face. In the preferred embodiment this restrictor blocks half of the keyway, exposing half of the head, and is located within one head width upstream of the head. The restrictor makes a flow angle in the range from 20 degrees to 60 degrees.

## Mechanism of Leveraging Bluff Body Motion into Piezoelectric Element Strain Energy

It is established that at certain flows wake instabilities will interact with mechanical resonance to result in Lock-in phenomenon. It is an object of the piezoelectric embodiment of this invention to provide a system with appropriate mechanical resonance frequency whilst not compromising the efficiency of leveraging the bluff head motion into piezo element strain energy. The embodiment can be described by a series of two complimentary levers that serve to gain down the bluff head dynamic motion, or likewise gain up the bluff head forces. The two series levers are the pivot arm lever, and the piezo element lever.

### Pivot Arm

It is an object of the pivot arm to lever the fluctuating flow forces on the bluff head into higher forces near the pivot point whilst being constrained to achieve an overall mechanical resonance frequency of the device. Correspondingly bluff head motions are leveraged down to smaller motions near the pivot point. Leveraging factors in the range of 25 are desirable. The pivot arm is substantially rigid when combined with the piezo element mechanical leveraging, resulting in the majority of the fluctuating strain energy residing in the piezoelectric elements. The pivot arm is supported by a flexure that provides the pivot point. The flexure is designed to allow up to 6 degrees of arm motion with very long life. The pivot arm centerline resides as far as possible from the conduit centerline, within mount support constraints yielding as low as possible losses from the arm motion in the flow. Near the outermost wall the flow is slowest, due to boundary layer and other turbulent effects of diverted flow at such Reynolds numbers.

While the pivot arm is substantially rigid its contribution to the overall mechanical resonance is substantially inertial, requiring that it be lightweight and strong in order to increase the overall device fluctuation frequency, or, for a given frequency, allow maximization of strain energy in the supporting element.

In an alternative embodiment this arm may be flexible in which case its design contributes both inertial and elastic effects to the design frequency. In this case the arm pivotal supports, essentially the levered piezo elements, are subject to less than the maximal available strain energy for a given head amplitude. While a flexible arm reduces the overall power generation performance it may be a desirable design feature for increasing the life of the device.

Further leveraging is required to match the available piezoelectric element stiffness, and therefore maximize the ensuing strain energy in the elements, to the leveraged pivot arm motions. This requires an efficient coupling near the point of rotation of the pivot arm. To accomplish this blade flexures are used. Blade flexures allow rotations about a design axis while allowing force to be transmitted along the axial length of the flexure. With the large bluff head motions caused by the lock-in phenomenon the blade flexures need to accommodate on the order of 6 degrees of pivot arm rotation. With careful design this is performed while ensuring long life of the flexures.

### Piezoelectric Element Mechanical Leveraging

The pivoting flexures transmit load to levered piezo elements. The levered elements are typically balanced on either side of the pivot arm as shown in Figure 7, although it is sufficient to have one on one side balanced by an appropriate load on the other. Leveraging is needed to achieve the necessary stiffness of the support such that the pivot arm responds in the desired frequency range.

It is the objective of the leverage to maximize the volume of piezo material, the strain energy stored in the piezo elements while providing the necessary stiffness. This aids the objective of generating power, as can be seen in the following relation,

$$P_{generated} \propto \eta_{conversion} \cdot \kappa^2_{coupling} \cdot \omega \cdot \int_V E_{strain}$$

where  $E_{strain}$  is the element strain energy,  $V$  is the piezo material volume,  $\omega$  is the frequency of fluctuating strain energy,  $\kappa^2$  is the squared material electromechanical coupling coefficient, and  $\eta$  is the effective electrical conversion efficiency from available piezoelectric electrical energy to desired load voltage and current.

To produce power at a given response frequency it is advantageous to maximize the volume integrated strain energy of the piezo elements. To maximize the volume of piezoelectric material that supports the pivot arm a mechanically efficient leveraging system is needed so that low stiffness can be realized from high stiffness elements. A preferred method to accomplish this is shown in Figure 8. Here two piezo stack elements are mounted between a rigid base and a single moving frame. The two elements are configured as stacks and are located in side by side with substantially the same cross sectional area and length with opposing ends connected to the moving frame. In this configuration the two elements share the gained load along their long axes, with the individual element displacements adding according to geometric constraints to give the displacement realized at the pivot arm connect point.

Piezoelectric stack elements are constructed by layering many thin wafers in mechanical series, but electrically in parallel [Ref [www.physikinstrumente.com](http://www.physikinstrumente.com)]. The thinner the layers the lower the stress induced voltages and higher the fluctuating stress induced currents. It is an object of this invention that stack construct is chosen judicious to be close to the required voltage and current of the eventual electrical load, see Figure 3b. If electrical conversion can be avoided by stack configuration, then this is the most efficient technique. Low power electrical converters have poor efficiency and may not work at all without sufficient current supply.

The rigid base of the device shown in Figure 8 is affixed to the conduit and the moving frame is connected to the pivot arm through a flexure with directional stiffness so as to transmit substantially longitudinal forces (Figure 8 shows this relative direction). The moving frame rotates relative to the base structure about an axis determined by a blade flexure. The flexure is formed with such stiffness as to allow relative geometric motions of the moving frame while supporting out of plane forces.

In the device shown in Figure 8 the mechanism leverages the resultant pivot arm forces into forces along the long axis of the piezo elements. The net leverage factor is approximately 15, so that the shared load factor is 7.5 for equivalent piezo element geometries, and therefore stiffnesses, sharing the applied load. The corresponding pivot arm displacements are levered down to small equivalent piezo element motions by the same factor. Overall device stiffness as seen by the pivot arm can be described by the following,

$$K_{out} = \eta_{frame} \frac{2K_{piezo}}{A^2}$$

where  $\eta_{frame}$  ranges between zero and one and is the cut down factor from the effect of finite moving frame stiffness,  $K_{piezo}$  is the piezo element stiffness and  $A^2$  is the squared lever factor. In the given design  $\eta_{frame}$  can be made to be nearly one by making the moving frame and base structure from very thick, rigid, constructions. In the preferred embodiment  $\eta_{frame}$  is greater than 0.8 so that the forces from the lock-in driven device are focused into the strain energy of the piezo elements.

The leveraging device is essentially similar to the device given in prior art (Hall, 5,907,211 shown in Figure 9) except that in this case only one frame is required. This alleviates a complicated mounting and support scenario as required for two pivotal frames.

The mechanistic gain in the device shown in Figure 8 comes to bear due to the small angle geometric arrangement of the moving frame that connects a rolling contacting area at one end of the first piezo element and the rolling contacting area at the opposing end of the second piezo element. The piezo elements each have rolling contact surfaces at both ends, connecting to both the moving frame and the rigid base structure. The piezo element rolling contacting surfaces are formed by a contacting ball end cap, with large radius as compared to the width of the piezo element, and central pinhole for alignment with the mount points.

Preload is applied to the contacting surfaces and piezo elements by pre stressing a beam, the tip of which is connecting to the larger displacement end of the moving frame. The preload acts across the rolling contact surfaces to axially pre compress the piezo elements. This is necessary to make the rolling contact surfaces efficient load carriers over small pivoting angles and is also necessary to render the lever capable of reacting bi-directional fluctuating forces.

The small angle made by the long axis of the piezo elements and the moving frame member in the shown device is approximately 7 degrees, corresponding to a leverage net gain factor of 7.5. Other gains are possible by reducing or increasing this angle, but practically smaller angles and larger gains are not reliable with this mechanism due to buckling considerations and packaging restrictions. Buckling comes into consideration due to the need for preloading the device to accommodate fluctuating loads and make the rolling contact ends of the piezo elements efficient load carriers. The piezo elements therefore experience twice the levered peak fluctuating loads plus some additional pre compression to accommodate surface contact.

Further consideration of the net maximum compressive loads needs to be given. A particular property of the bulk piezoelectric material is that it will de-pole when compressed with enough stress. De-poling is where the material loses its fundamental piezoelectric behavior and, for example, the coupling coefficient effectively reduces to a small quantity. All compositions exhibit this behavior under sufficient stress and stack constructions can be particularly prone to de poling depending on the nature of the residual three-dimensional stresses of manufacture. The elements maybe re-poled by exposing the material to sufficient polar voltage and at elevated temperatures, but in subterranean applications this is not practical.

A selection of materials to maximize coupling coefficient is also advantageous. The coupling coefficient is best when the material is loaded in the same direction that it is poled. In a stack configuration this is the mode of operation. Typically the  $\kappa^2$  is of the order 0.5 for soft piezoelectric compositions as is reported in "Important Properties of Morgan Matroc Piezoelectric Ceramics," TP - 226, Morgan Matroc Inc. Higher coupling coefficients are possible with single crystal piezoelectric materials as is reported in "Characteristics of Relaxor-Based Piezoelectric Single Crystals for Ultrasonic Transducers," *IEEE Trans. on Ultrasonics, Ferroelect. and Freq. Control*, 44(5):1140-1147 (September 1997). However, the later are restricted to lower temperature operations due to the lower Currie temperatures of the material.

As is shown in Figure 9 there are several ways to achieve the stiffness reduction and efficient leveraging from the fluctuating pivot arm motion to piezo electric strain energy. Another leveraging mechanism is shown in Figure 10. Here a double lever is formed in a single body of material by making appropriate cuts to leave stiff regions and flexing regions. There are now two flexural points of rotation. The gain is, as before, determined by the geometric arrangement of the piezo elements and the rotation points. In this case the rotation function has been separated into to flexures and brought closer to the motional end allowing the device to be made inexpensively from a single piece of material.

The piezo elements now essentially reside in a pocket cut into the piece. They form rolling contacts with the supporting ends of the piece allowing the realization of the geometric gain.

As in device of Figure 8 (and Figure 9) a preload beam may be used to apply load to the device via mechanical adjustment. The beam is pre stressed against the based structure in and applies load to the device in such a way as to pre compress the rolling contact and, in turn, the piezo elements.

Different scales of the lever are possible. For example, if the levered piezos are mounted further from the pivot point a softer lever is needed to keep the same mechanical resonance frequency (for a given head and pivot arm length etc because it is necessary to maintain the same rotational stiffness as seen by the pivot arm). A softer lever could be realized by piezo elements with smaller cross section area. At the outward mounted location the device displacements are higher and resulting higher strains, but the combined effect of reduced stiffness and larger strains exactly balance to yield the same strain energy. But we have reduced the volume of piezo material therefore reducing the power produced and eventually we will not be able to support the necessary loads because the elements will be too long and too thin.

Conversely if were possible to mount closer to the pivot a stiffer lever could be used. More piezo material cross section will allow this but smaller displacements result nearer the pivot point, and therefore strains have reduced and as before the net strain energy is unchanged. However, in this case, we have increased the piezo material volume improving the overall power production. The device shown in Figure 7 represents a compromise between packaging constraints and maximizing the piezo material volume for a given strain energy.

If the pivot arm were to be made longer, and thus with increased inertia, the piezo lever stiffness would need to be increased to maintain resonance frequency and therefore there would be volumetric gains. However, the bluff head is constrained to displace within certain amplitudes defined by the flow channeling, and therefore the longer the arm the

smaller the maximum amplitude of lever motion. If the arm length was doubled then four times the stiffness is needed to maintain resonance frequency, but correspondingly only one half the driven displacements are now available, and therefore there is no increase in strain energy. Theoretically we would have gained by implementing a stiffer lever by increasing the piezo material volume, but within packaging constraints this is not possible.

## Mechanism of Leveraging Bluff Body Motion into Magnetically

It is established that at certain flows wake instabilities will interact with mechanical resonance to result in Lock-in phenomenon. It is an object of the magnetic embodiment of this invention to provide a system with appropriate mechanical resonance frequency whilst not compromising leveraging of the bluff head motion into dynamic magnetic flux changes within a coil. One way to do this is pass a strong magnet in and out of a fixed position coil. The embodiment can be described as a pivot arm with inertia complimented by elastic support means to give a mechanical resonance consistent with lock-in wake frequencies.

In the magnetic embodiment power is achieved through the translation of a magnet through a coil to produce a voltage. Attaching a flexure to a beam, constraining one end of the flexure and utilizing the flexures rotational spring constant to obtain a desired frequency of the system accomplishes this. The total moment of inertia for the system can be determined by the combination of contributions from the bluff body, the magnets and the pivot arm that connects them to the elastic means. The moment of inertia is then used to determine the required rotational spring constant

$$f = (1/2\pi) * ((K\theta / I)^{.5})$$

It is desirable to use permanent magnet material with as high as energy density as possible, such as Neodymium-iron-boron, so that the inertia effects from the magnet material can be reduced. In this way the frequency and amplitude of the device can be maximized. Knowing that the frequency target is produced by the Strouhal relation for a given flow rate, the required rotational spring constant for the system can be found. Using this required rotation spring constant, the required area moment of inertia for the flexure is

$$I_{flexure} = (K\theta * L_f) / E$$

Where  $L_f$  is the length of the flexure and  $E$  is Young's modulus for steel of which the entire system is constructed. The flexure must also be designed for life. The strains computed for a given displacement of the pivoting bluff body section can be computed and used as a constraint to keep the flexure stresses within a long life range.

An implemented design is shown in Figure 3d.

The maximum magnetic flux for given permanent magnet can be approximately calculated.

$$\phi_{max} = B * A$$

Assuming a sinusoidal output for the system, the magnetics can be modeled as follows:

$$d\phi/dt = \phi_{max} * \omega * (\sin(\omega t))$$

The voltage produced in a coil of  $N$  turns is simply then:

$$V = N * (d\phi/dt)$$

by Lenz's law. The number of turns of the coil will play a major role in the voltage output for a given load resistance across the output leads.

In reality, lock-in displacements will not produce a sine wave voltage, but rather a rectified sine wave due to the fact that the magnet will not go all the way through the coil. The magnet will enter to some distance then retreat. An

example calculation for a 0.5 T Neodymium-iron-boron magnet (1/4 inch diameter) displacing into a 2500 turn coil produces roughly 2 Volts.

## Demonstration

A success mode of operation has been found. The conduit inner diameter is approximately 2.85 inches. The keyway width is 2 inches and it is of order 3 feet long. When cut into a 5.25 inch OD section the keyway makes a slightly greater than 1.25 inch depth. A substantially long, greater than 12 inch, ramp that expands core flow into the keyway is employed at the upstream end. Down stream from the keyway expander, prior to the bluff body head is a local flow restrictor. The local flow restrictor is about 1 inch long and forms nearly a 45 degree wedge that restricts half of the keyway width and marginally more than the keyway height.

The bluff body head spans slightly more than the height of the keyway and is on order 0.7 inches wide. It is located in the center of the beam width of the keyway about one head width down stream from the restrictor. The head width and stream wise length are of the same order of dimension.

## Piezoelectric Means

The pivot arm that supports the bluff head spans 7 inches to its pivot point. It is substantially rigid. The flexures that support the arm are designed for long life while supported over 6 degrees of peak rotation amplitude. The piezo levers are mounted annularly at the pivot arm base, on each side of the pivot arm, and are affixed with distance 0.25 inches from the pivot point. The piezo levers individually have roughly 500 lb/in stiffness giving a net of roughly 60 lb-in rotational stiffness at the pivot point.

Core flows on the order of 150 GPM yield half the local flow speed in the keyway. The lock-in frequency achieved is 10-12 Hz. Lock-in is witnessed at flows from 130 to 300+ GPM. At 170 GPM roughly 16-20 mWatts of power is produced. Power is measured by rectifying the piezoelectric output with piezo elements from each side connected in series. Output voltages on the order of 10 Volts were measured with 2 milliAmperes of net current.

At 150 GPM a pressure drop of 0.125 psi was measured across the whole section. At 210 GPM 0.5 psi pressure drop was measures.

## Magnetic Means

A prototype magnetic means has been constructed and bench top tested. The arm that supports the bluff head and the permanent magnets is approximately 14 inches long. It is designed to sit wholly within the channels of type shown in Figures 7. In the case of this lock-in device the channel would be long enough to allow the motion of the bluff body and the permanent magnet end. A similar entryway ramp and a local flow diversion would be used to engage the bluff body head with flow. Flow once sufficiently downstream of the bluff body head (approx. 4 inches) can be diverted back to the core conduit, as is the case before the piezo mechanisms in Figures 7, rather than flow around the permanent magnet end causing deleterious effects.

Bench top measurements have been made. The coil shown in Figure 3d was appropriately located and the flapper displaced by hand and allowed to ring down in free resonance fashion. The magnet is Neodymium-iron-boron and measures 0.5 T. Simple tests generated approximately 2.44 Volts peak output when loaded by a 100 Ohm resistor (24 mAmps peak). Displacements were approximately half of that expected in the flow rig, so we may expect this to be considerably higher. This test only used a coil on one side of the device, notice that there are magnets bonded to both sides, so that the output power can roughly be doubled.

## Other Embodiments

In a further embodiment of this invention flow restrictions may be added to the inner diameter of the core conduit in the vicinity of the keyway. In this way higher local flow velocities can be achieved at the expense of pressure

drop across the overall section. One way to achieve this is shown in Figure 11. In this case rings of 1/8<sup>th</sup> inch thickness are placed along a length of the inner diameter of the conduit. Flow is diverted, as is shown by analysis and practice, into the keyway and speeds are higher near the bluff head. Another way under investigation is to provide a spring loaded cover that extends across the conduit bore when loaded by flow pressure and retracts when pushed from the down stream side.

In further embodiments bluff body heads of various shapes are possible. Figure 12 shows several of which that worked to substantially the same extent.

In a further embodiment an upstream wake excitation device maybe employed to aid in lock-in device excitation. For example the flow restrictor located just upstream of the bluff head may itself buffet in the flow shedding vortices that aid the loc-in phenomenon.

In a further embodiment the flow maybe completely separated off from the core conduit flow before impinging on the bluff body head. As mentioned before conduit flow restrictors or retractable diverter plates may be used.

In a further embodiment of the piezoelectric means single crystal relaxor piezoelectric materials are employed to utilize higher coupling coefficients. Relaxor piezoelectric materials include, for example,  $\text{Pb}(\text{Zr}_{1-x}\text{Nb}_x)\text{O}_3$ - $\text{PbTiO}_3$  (PZN-PT) and  $\text{Pb}(\text{Mg}_{1-x}\text{Nb}_x)\text{O}_3$ - $\text{PbTiO}_3$  (PMN-PT), and are described in detail in Park & Shrout, "Characteristics of Relaxor-Based Piezoelectric Single Crystals for Ultrasonic Transducers," *IEEE Trans. on Ultrasonics, Ferroelect. and Freq. Control*, 44(5):1140-1147 (September 1997), which is incorporated herein by reference. To illustrate the difference between polycrystalline and single crystal piezoelectric material, Table 1 lists selected characteristics of each for some PZN-PT compositions. Note the generally higher coupling coefficients of single crystal material, and the highly coupled compliance and modulus (as evidenced by the ratio of the 13 terms to the 33 terms).

In a further embodiment the piezoelectric elastic means and the magnet means are combined and the extracted power combined to provide a generated source of power.

In a further embodiment of the magnetic means other types of permanent magnet material is used. A selection being from the following typical permanent magnet materials: 36 Co Steel, Alnico, Remalloy, Vicalloy, Samarium-cobalt, Neodymium-iron-boron. The later being preferable due to its energy density.

In a further embodiment of the magnetic means the coils maybe affixed to the moving arm and the permanent magnets affixed in an appropriate relative position on the conduit.

Material	Strain-field coupling, $d_{33}, d_{31}$ (pm/V)	Charge- strain coupling, $g_{33}, g_{31}$ (mV-m/N)	Coupling coefficient, $k_{33}, k_{31}$	Short-circuit modulus, $c_{33}^E, c_{11}^E, c_{12}^E, c_{13}^E$ ( $\times 10^{10}$ N/m <sup>2</sup> )	Short-circuit compliance, $s_{33}^E, s_{11}^E, s_{12}^E, s_{13}^E$ ( $\times 10^{-12}$ N/m <sup>2</sup> )
PZT-4*	289, -123	26, -11	0.70, -0.33	11.5, 13.9, 7.8, 7.4	15.5, 12.3, -4.0, -5.3
PZT-5H*	593, -274	20, -9	0.75, -0.39	11.7, 12.6, 8.0, 8.4	20.7, 16.5, -4.8, -8.4
Single Crystal <sup>#</sup>	2000, -1000	44, -21	0.91, -0.50	10.5, 11.1, 10.1, 10.5	108.0, 82.0, -28.5, -51.0

**Table 1: Properties of selected piezo electric materials**

Notation is standard IEEE notation for piezoelectricity. Material is transversely isotropic. Cut quoted by manufacturer is <100>.

\*data according to Morgan Matroc, Inc. TP-226

<sup>#</sup>data according to TRS Ceramics for PZN-4.5%PT, Inc. <http://www.trsceramics.com>

**(f) Claim or claims.**

What is claimed is:

1. A lock-in power generator comprised of
  - a fluid conduit configured for flow of fluid therethrough; and
  - a bluff body residing in the conduit, the bluff body being exposed to the flow from which it sheds unstable vortices in its wake, the bluff body being supported by flexible means, and the bluff body being configured such that it can move in relation to the fluctuating forces generated on the body in response to the vortex shedding;
    - a flexible support means that, when combined with the overall inertia of the moving body and support, gives rise to a mechanical resonance, the mechanical resonance frequency being consistent with the shed wake frequency over a desired range of flow;
    - a plurality of piezoelectric elements comprising a substantial portion of the flexibility of the flexible support means, the piezoelectric elements generating electricity in response to the fluctuating strain induced by the locking-in of the wake frequency and the mechanical resonance.
2. The generator according to Claim 1 wherein the fluid conduit is a pipe such as that used in subterranean oil and gas production, wherein the fluid flow is a mixture of hydrocarbons, water and gas constituents.
3. The generator according to Claim 1 wherein the bluff body substantially resides in a cutaway section that resides adjacent to, but not disjoint from, the main core of the conduit such that the core flow is largely unobstructed, the section being an essentially expansion of the core flow over a limited fraction of the annulus, the section entry and exit being designed to maximize the flow speed impinging on the bluff body head.
4. The generator of Claim 3 where a local flow restrictor is placed just upstream of the bluff body in the cutaway section so as to raise local flow velocity prior to it impinging on the body.

5. The generator of Claim 3 where flow restrictors are placed in the path of the core flow in such away as to restrict core flow and therefore create higher flow speeds in the cutaway section where the bluff body resides.
6. The generator according to Claim 1 wherein the bluff body substantially resides in a completely separated flow section that resides disjoint from and along side the main conduit such that the core is unobstructed.
7. The generator of Claim 6 where flow restrictors are placed in the path of the core flow in such away as to restrict core flow and therefore create higher flow speeds in the separated section where the bluff body resides.
8. The generator of Claim 6 where a local flow restrictor is placed just upstream of the bluff body in the separated flow section so as to raise local flow velocity prior to it impinging on the body.
9. The generator of Claim 1 where the bluff body cross section shape is designed to maximize the sensitivity of the lock-in phenomenon, the bluff body having at least one face making an incident angle with the local flow, the body having edges or substantial surface gradients with respect to the flow such that vortices may be shed downstream, the body having substantial surface area downstream of the location of vortex detachment such that the alternating shed vortices cause fluctuating reaction forces against the body.
10. The generator of Claim 1 where the bluff body is supported by pivoting arm that is substantially rigid with respect to the flexible means that supports the rotation of the arm.
11. The generator of Claim 10 where the support arm is designed to reside in a region of flow which is lower than the average flow speed impinging on the bluff body thus minimizing the effects of the arm geometry on the lock-in phenomenon. The arm residing substantially in the boundary layer of the expanded flow.
12. The generator of Claim 1 where the bluff body is supported by a flexible arm such as a beam the bends in response to the lock-in induced forces. The beam sharing the strain energy with

leveraged piezoelectric means that supports it, either mounted geometrically supporting the beam or residing wholly within a separate leveraging mechanism.

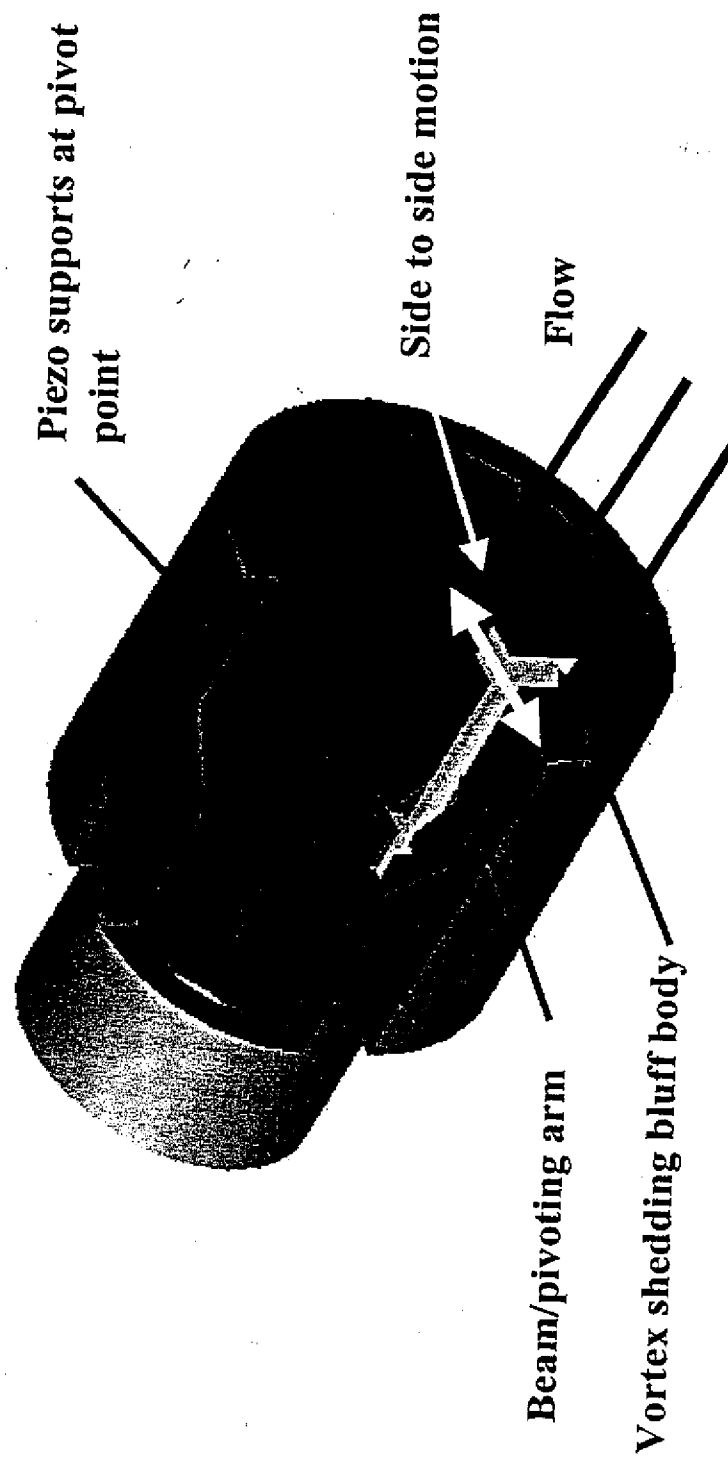
13. The generator of Claim 1 where the piezoelectric elements are combined with essentially rigid elements to provide leveraged flexible supporting means, the supports having such stiffness, when mounted in appropriate location, so as to interact with the system inertia to yield a mechanical resonance that locks-in with the wake frequency over a desirable rang of flows.
14. The generator of Claim 13 where the leveraging means comprises of one moving frame and a rigid supporting base, the moving frame being mounted by flexure to the rigid base so as to provide geometric leveraging of the pivot arm motion into piezoelectric element strains, the piezoelectric element ends being mounted via rolling contacts between the moving frame and the rigid base, the combined piezoelectric elements and moving frame system being preloaded by an external spring so as to engage the rolling contact surfaces and significantly load the overall system to accommodate the motion induced by fluctuating loads applied to the moving frame end.
15. The generator of Claim 13 where the leveraging means comprises of that given in Prior Art, US 5,907,211.
16. The generator of Claim 13 where the leveraging means comprises of a single body of material cut to support (one or) two independent piezoelectric elements, the body being substantially rigid apart from two independent flexures that support rotation of the body elements relative to the piezoelectric elements, the flexures supporting substantial load transfer along their length while allowing rotation that results in high geometrical gain factor from applied body motion to piezoelectric element strain, the piezoelectric elements mounted to the body through rolling contacts that essentially transfer only axial load to the elements and are made effectual through application of pre load, the body being wholly supported in the region of one end of one piezoelectric element and the other body parts, as connected by flexures and the piezoelectric elements, moving in concert with the applied forces to the adjacent body section.

## \*\*\*\*\*Claims pertaining to magnetic means\*\*\*\*\*

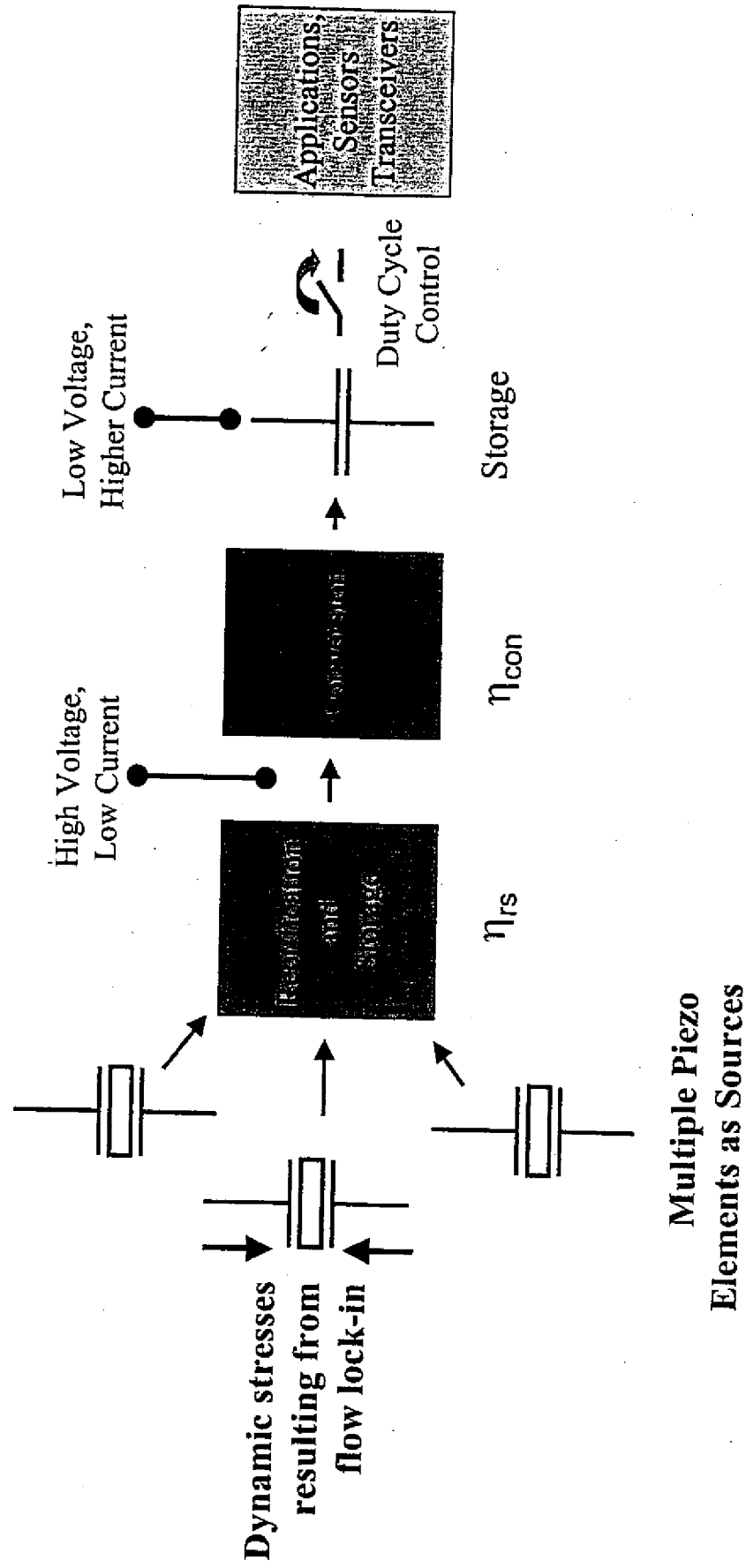
17. A lock-in power generator comprised of:
  - a fluid conduit configured for flow of fluid therethrough; and
  - a bluff body residing in the conduit, the bluff body being exposed to the flow from which it sheds unstable vortices in its wake, the bluff body being supported by flexible means, and the bluff body being configured such that it can move in relation to the fluctuating forces generated on the body in response to the vortex shedding;
  - a flexible support means that, when combined with the overall inertia of the moving body, gives rise to a mechanical resonance, the mechanical resonance frequency being consistent with the shed wake frequency over a desired range of flow;
  - a plurality of permanent magnetic elements and wire coils mounted relative to each other on the motional parts and corresponding locations in the conduit such that flow forces induce relative motions between the magnetic elements and the coils generating electrical potential and current flow in the coils.
18. The generator according to Claim 17 wherein the fluid conduit is a pipe such as that used in subterranean oil and gas production, wherein the fluid flow is a mixture of hydrocarbons, water and gas constituents.
19. The generator according to Claim 17 wherein the bluff body substantially resides in a cutaway section that resides adjacent to, but not disjoint from, the main core of the conduit such that the core flow is largely unobstructed, the section being an essentially expansion of the core flow over a limited fraction of the annulus, the section entry and exit being designed to maximize the flow speed impinging on the bluff body head.
20. The generator of Claim 17 where a local flow restrictor is placed just upstream of the bluff body in the cutaway section so as to raise local flow velocity prior to it impinging on the body.
21. The generator of Claim 17 where flow restrictors are placed in the path of the core flow in such away as to restrict core flow and therefore create higher flow speeds in the cutaway section where the bluff body resides.

22. The generator according to Claim 17 wherein the bluff body substantially resides in a completely separated flow section that resides disjoint from and along side the main conduit such that the core is unobstructed.
23. The generator of Claim 22 where flow restrictors are placed in the path of the core flow in such away as to restrict core flow and therefore create higher flow speeds in the separated section where the bluff body resides.
24. The generator of Claim 22 where a local flow restrictor is placed just upstream of the bluff body in the separated flow section so as to raise local flow velocity prior to it impinging on the body.
25. The generator of Claim 17 where the bluff body cross section shape is designed to maximize the sensitivity of the lock-in phenomenon, the bluff body having at least one face making an incident angle with the local flow, the body having edges or substantial surface gradients with respect to the flow such that vortices may be shed downstream, the body having substantial surface area downstream of the location of vortex detachment such that the alternating shed vortices cause fluctuating reaction forces against the body.
26. The generator of Claim 17 where the bluff body is supported by pivoting arm that is substantially rigid with respect to the flexible means that supports the rotation of the arm.
27. The generator of Claim 26 where the support arm is designed to reside in a region of flow which is lower than the average flow speed impinging on the bluff body thus minimizing the effects of the arm geometry on the lock-in phenomenon. The arm residing substantially in the boundary layer of the expanded flow.
28. The generator of Claim 17 where the bluff body is supported by a flexible arm such as a beam that bends in response to the lock-in induced forces. The beam sharing the strain energy with means that supports it.
29. The generator of Claim 17 where the permanent magnet elements reside in a location to maximize the relative rate of change of displacement between the elements and corresponding wire coils, within the conduit flow path limitations.

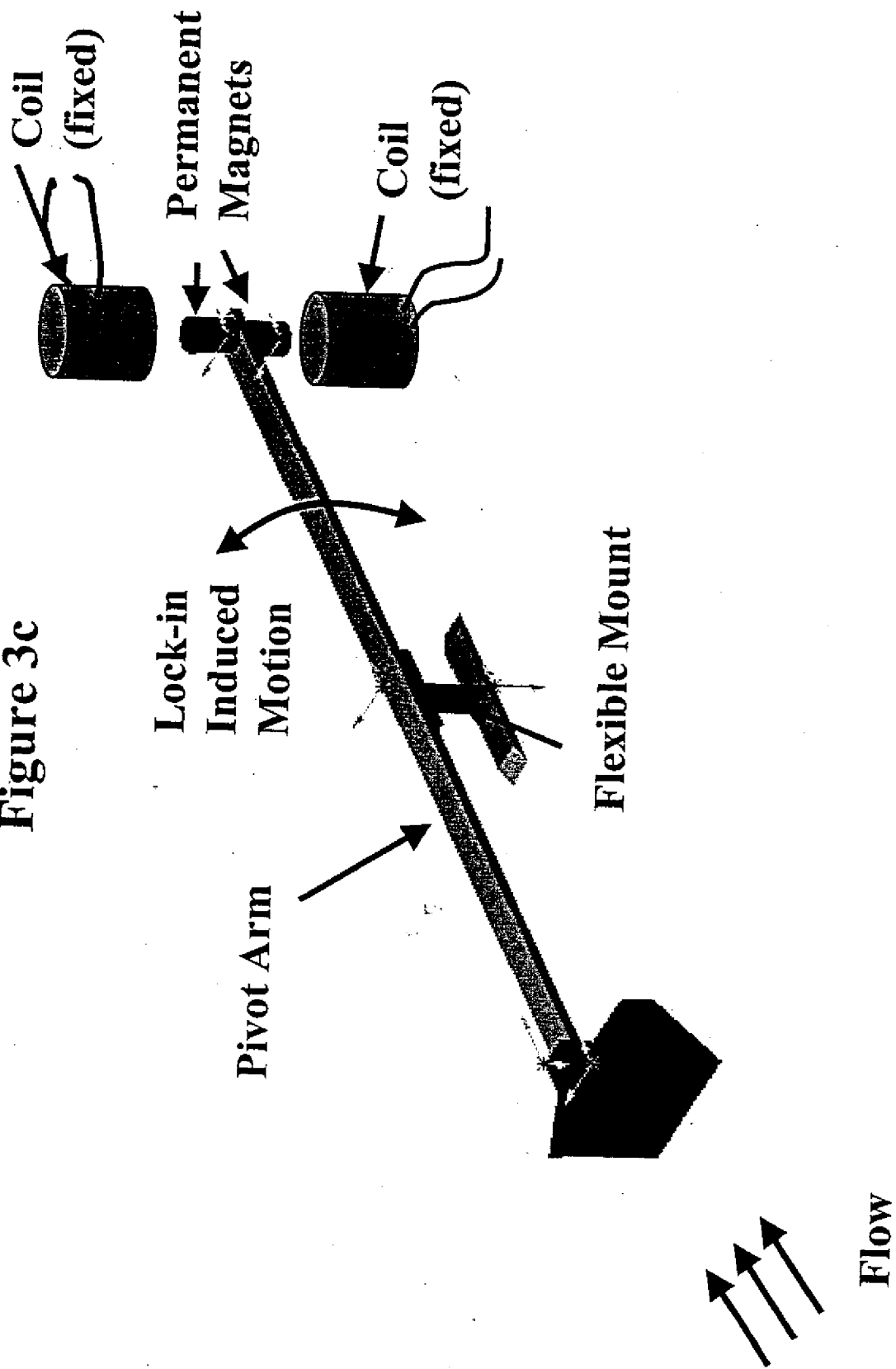
**Figure 3a**



**Figure 3b**



**Figure 3c**



**Figure 3d**

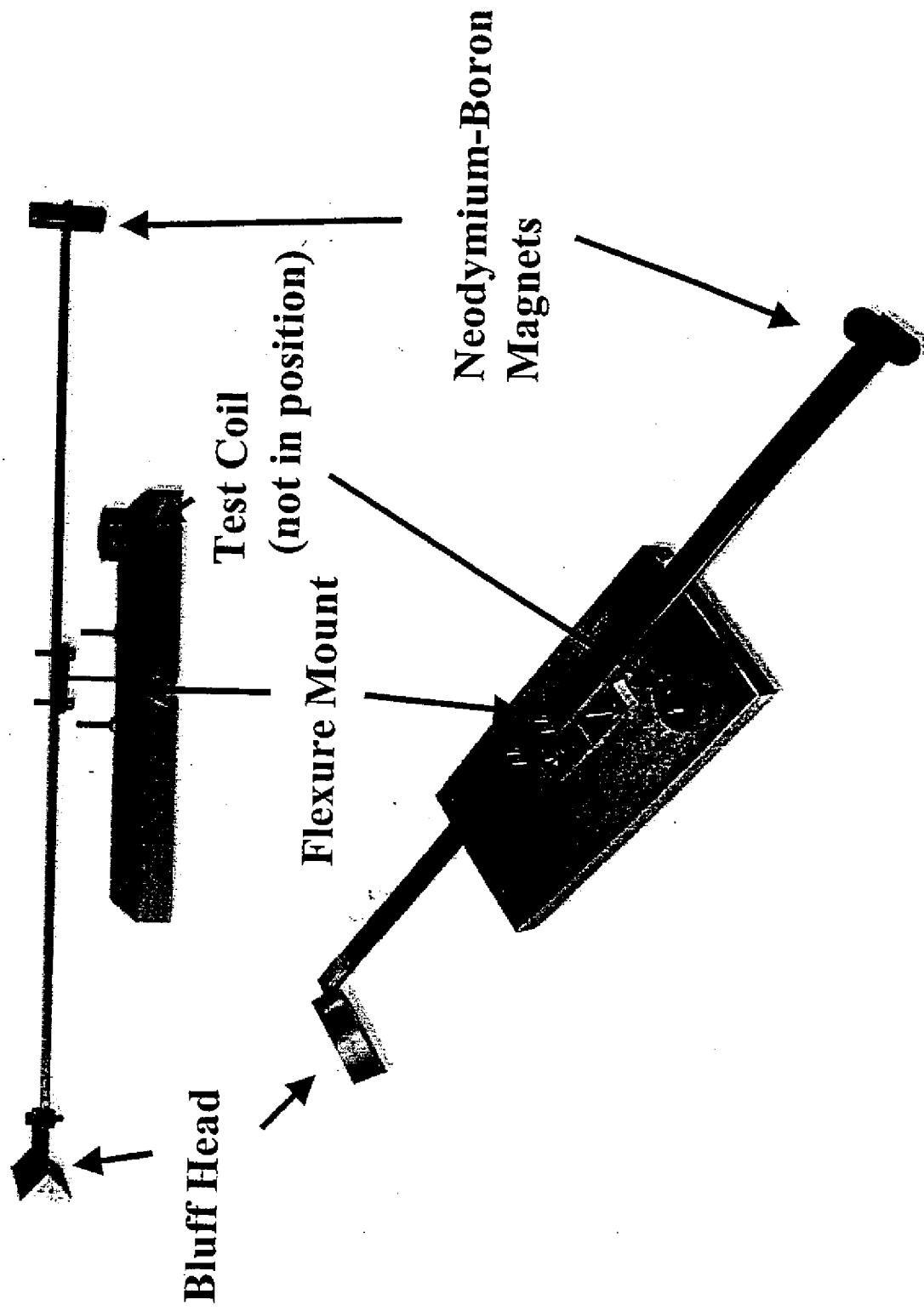


Figure 4

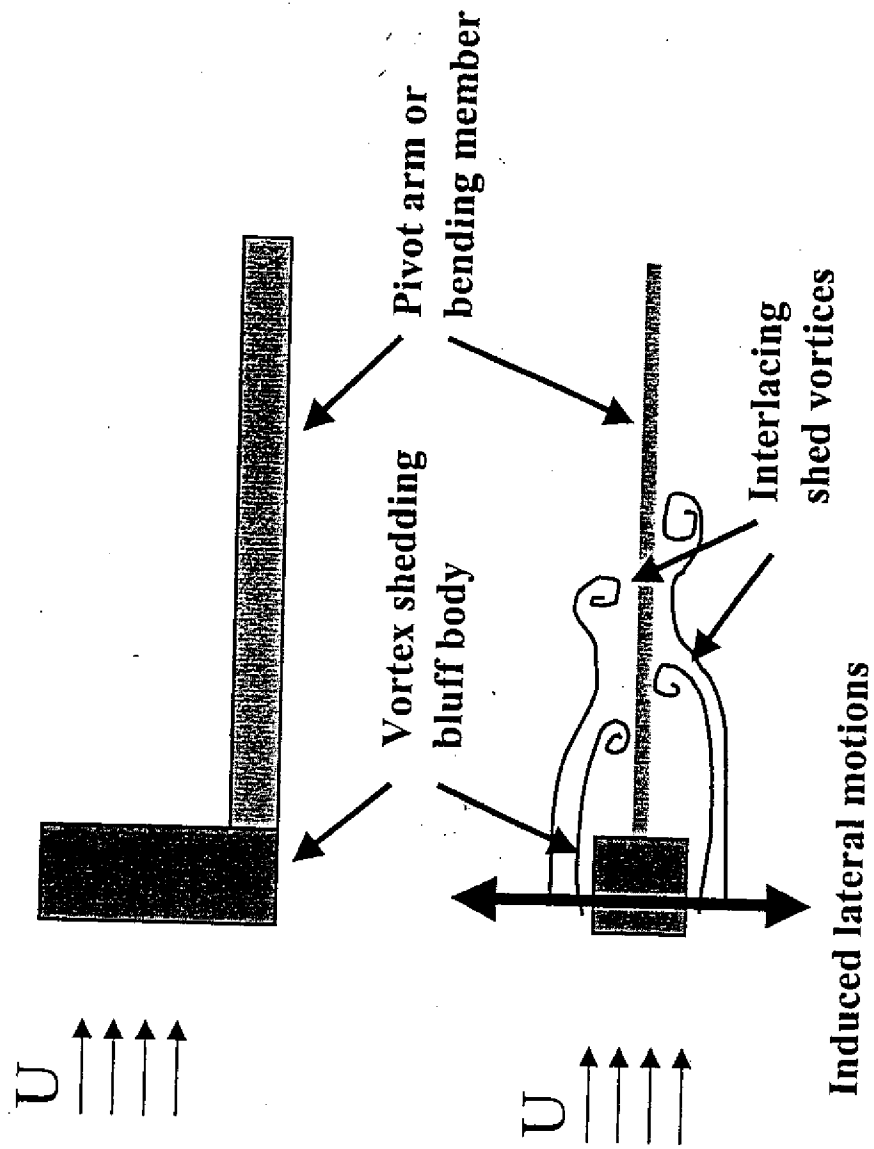
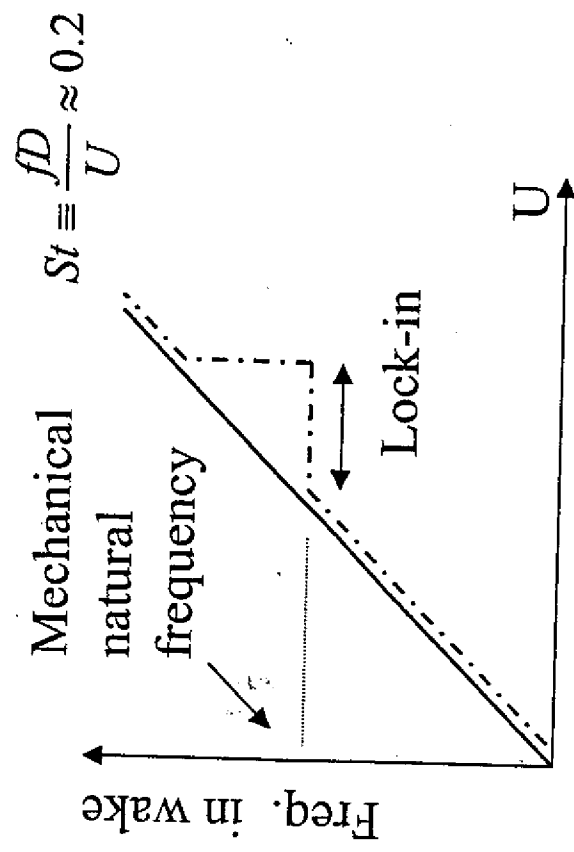
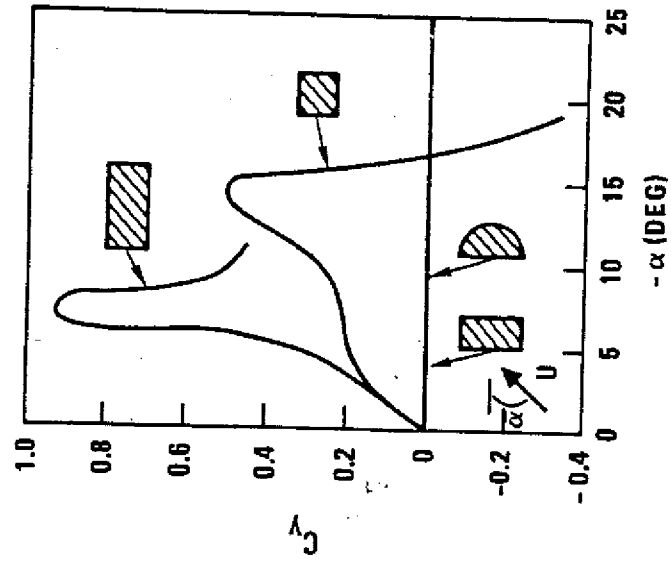


Figure 5

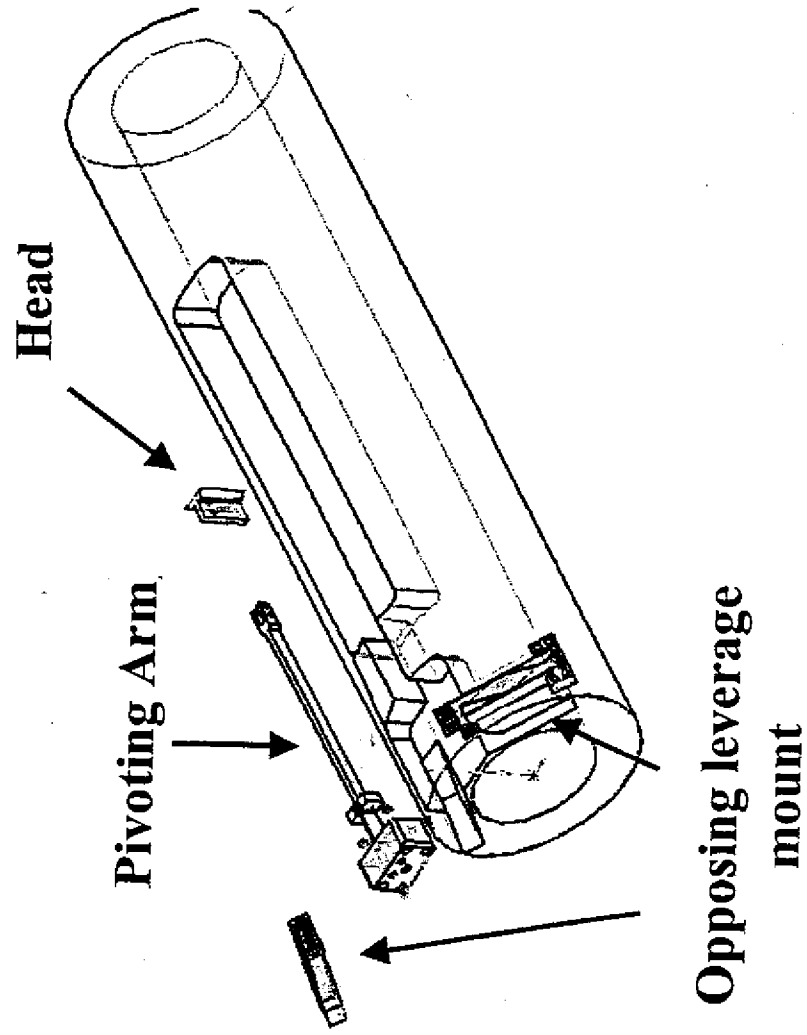


**Figure 6**

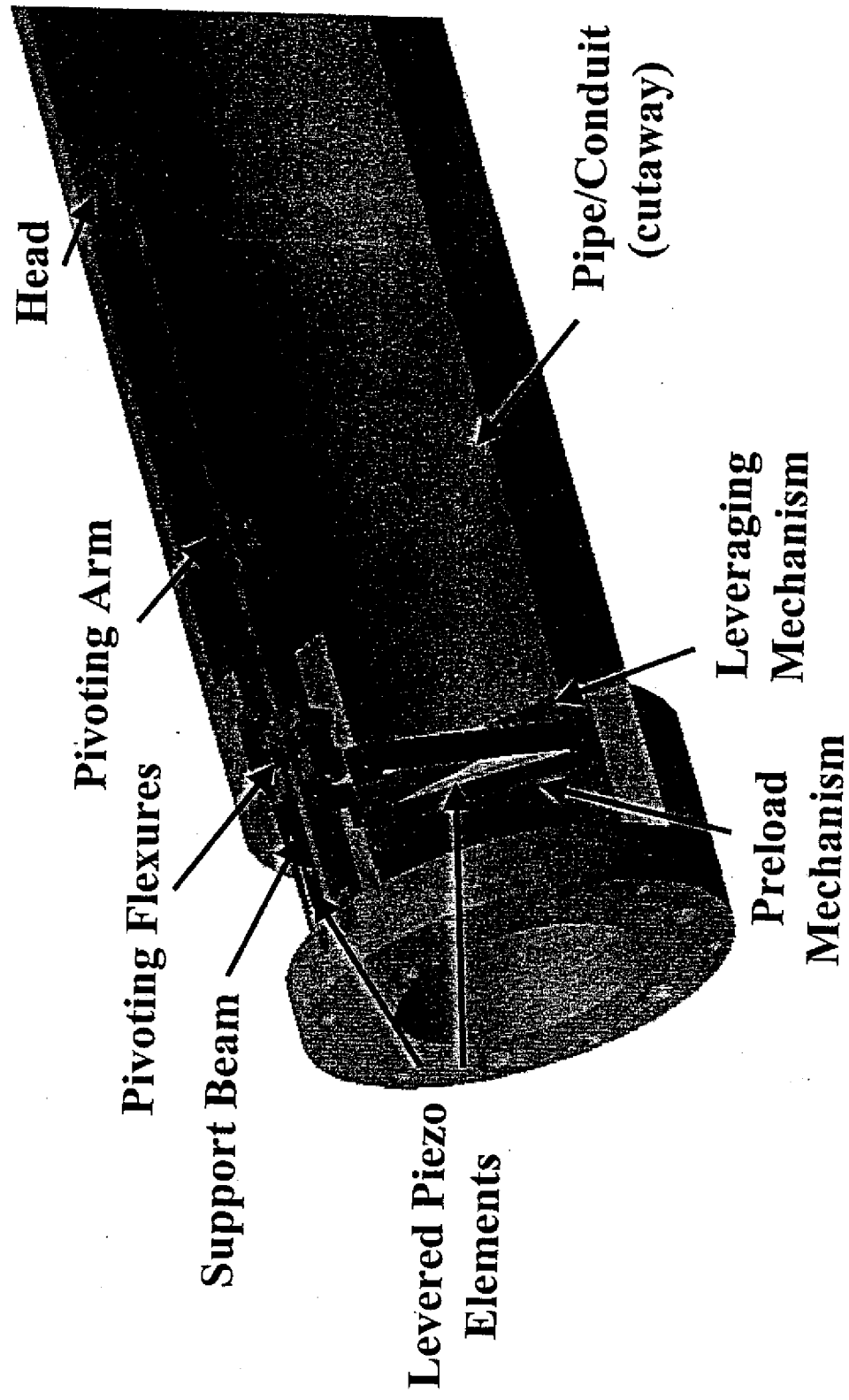


**Lift coefficient plot from Blevins  
for varying body shapes (in air)**

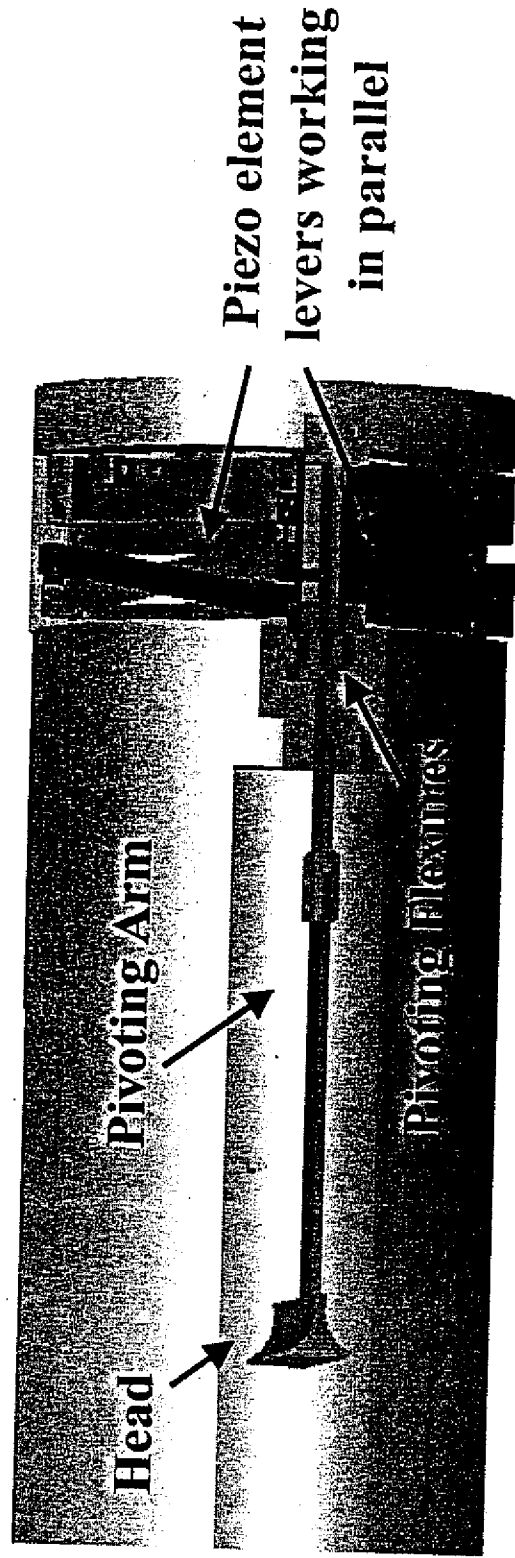
**Figure 7**



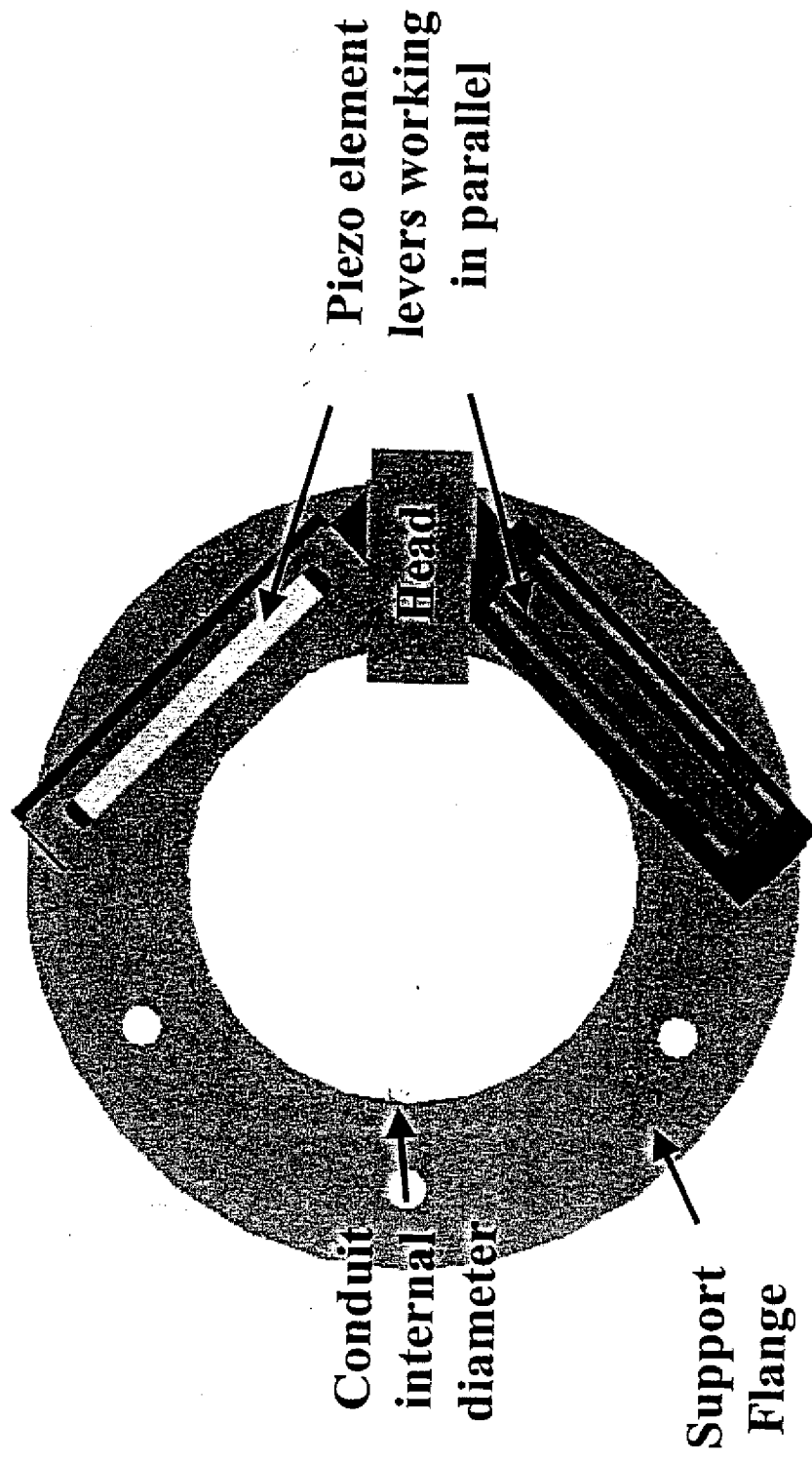
**Figure 7b**



**Figure 7c**

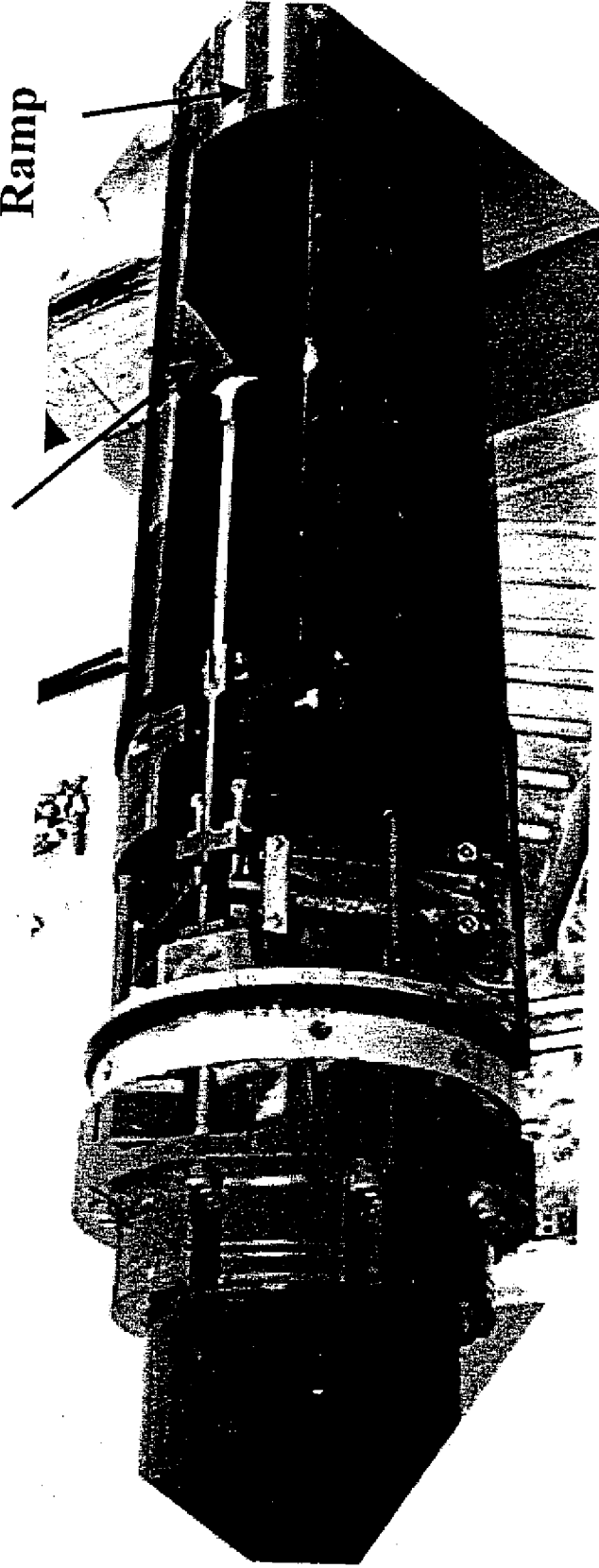


**Figure 7d**

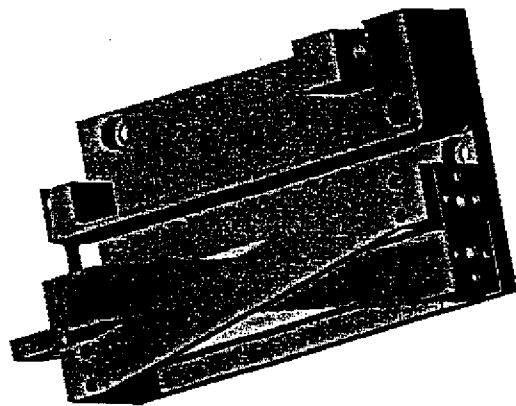
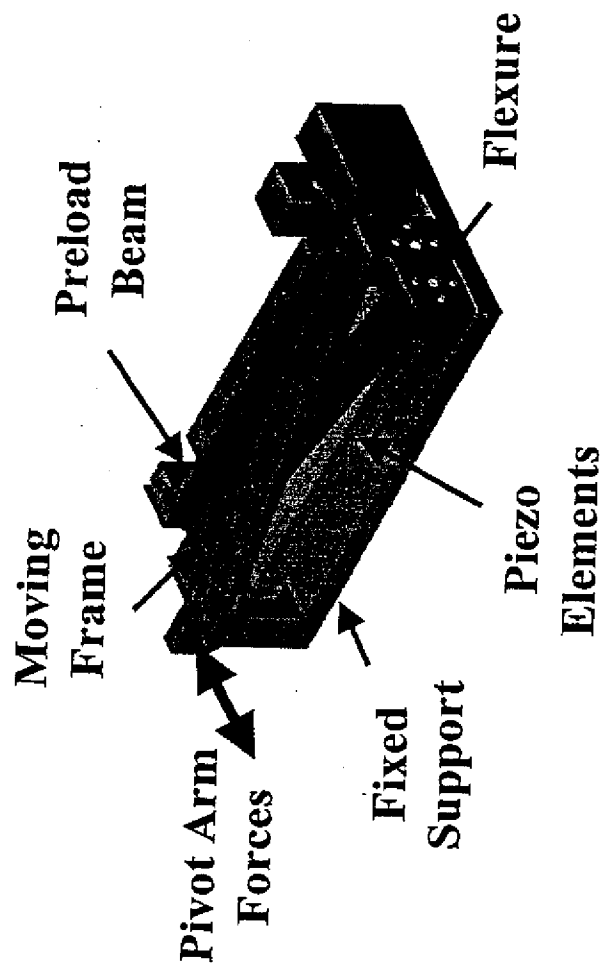


**Figure 7e**

**Local Restrictor**      **End of Keyway**  
**Ramp**

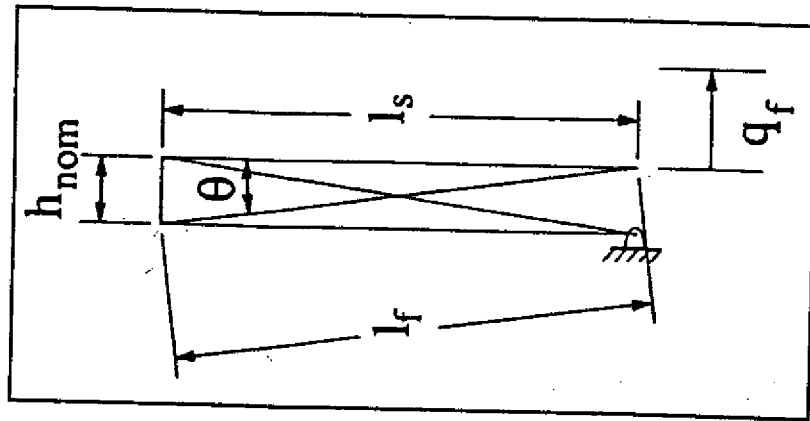
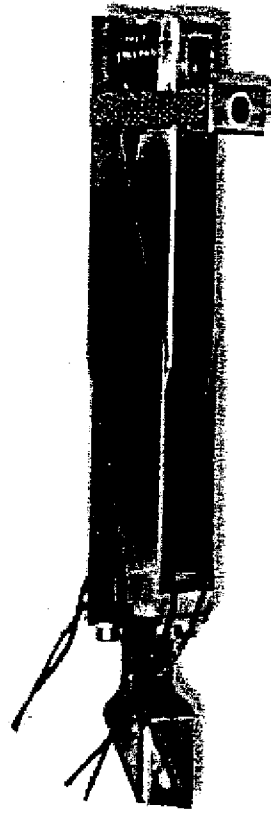
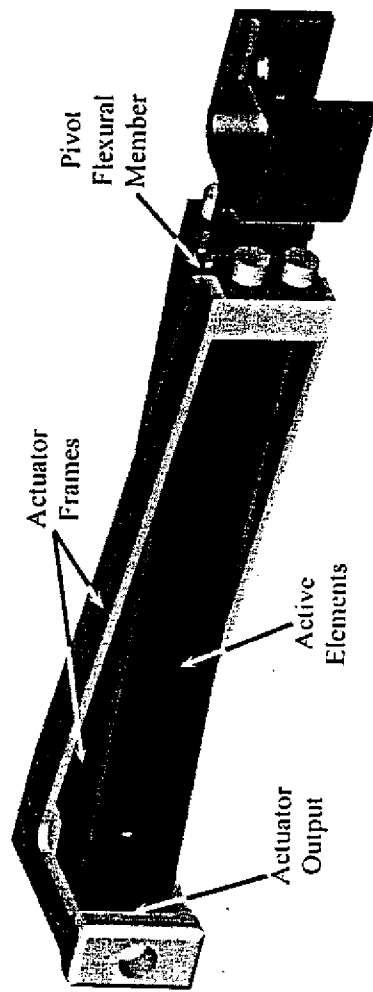


**Figure 8**

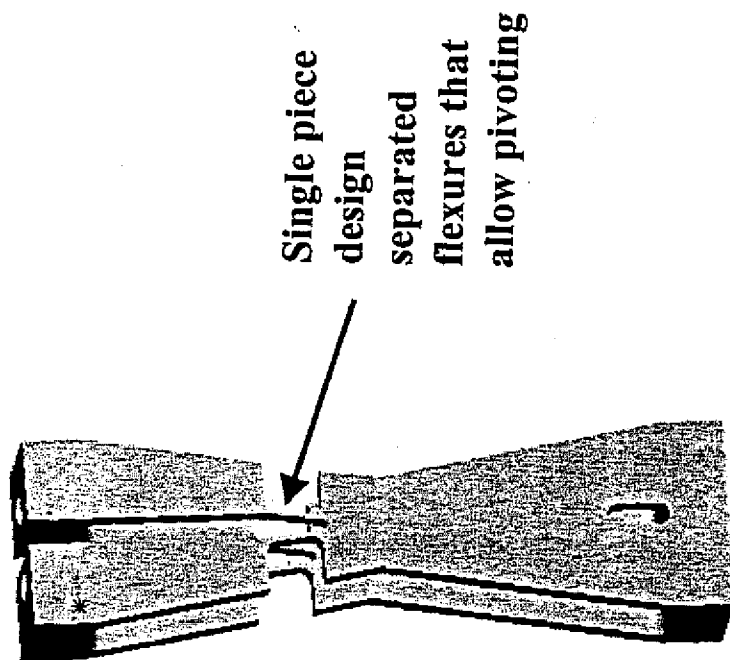


**Figure 9**

**Two pivotal frames – Figure 1  
from US 5,907,211, shown below  
with flexure at pivoting frame  
ends.**



**Figure 10**



# Figure 11a

slinerestrictor3b-slineresrictor3 :: Fluid Flow  
Units : m/sec Deformation Scale 1 : 0

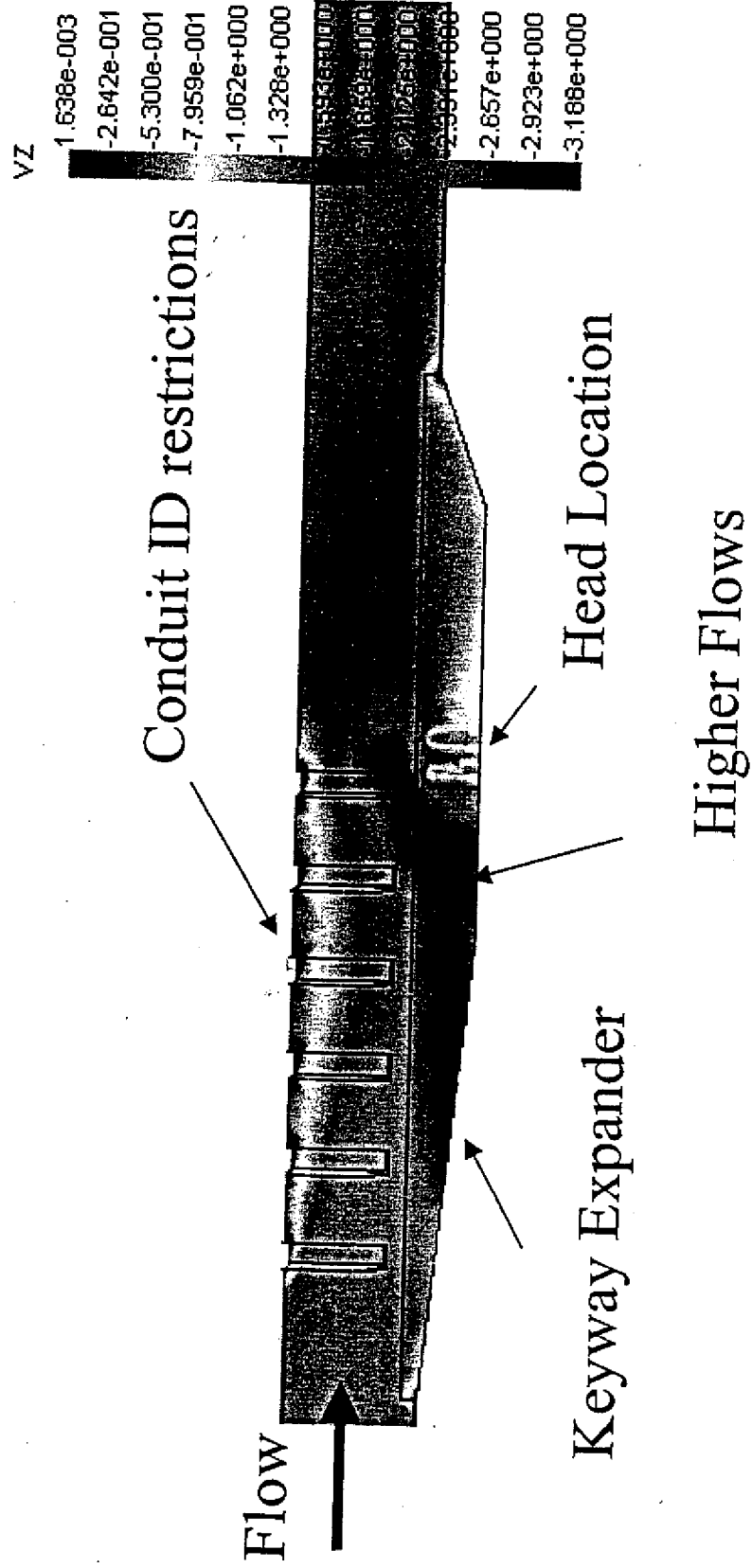
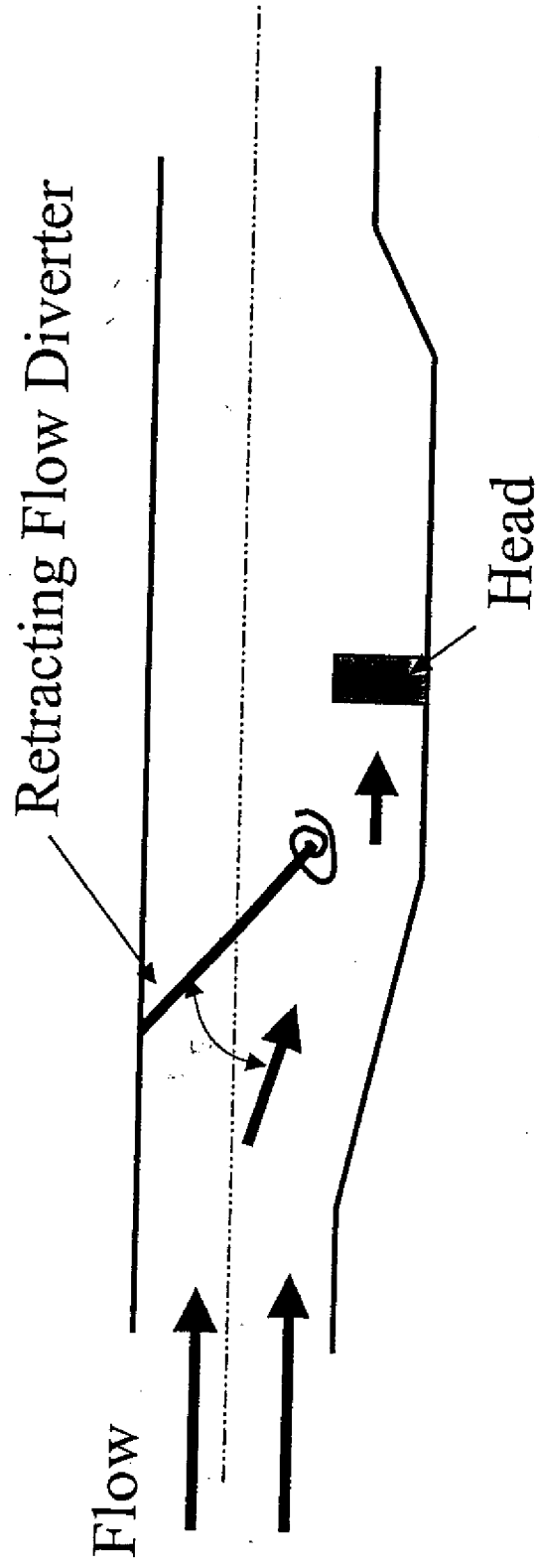
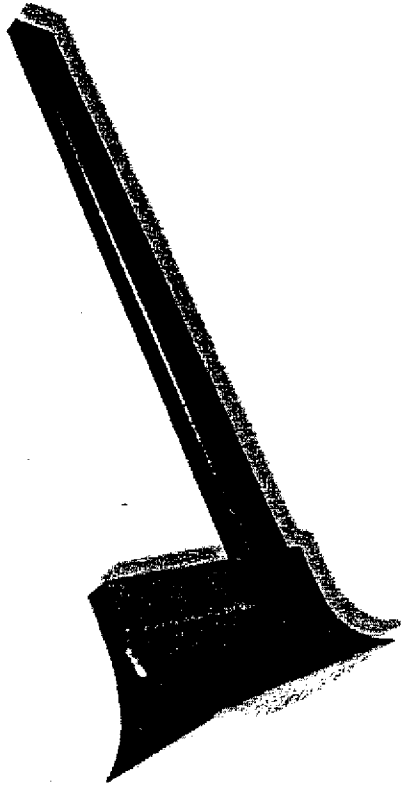


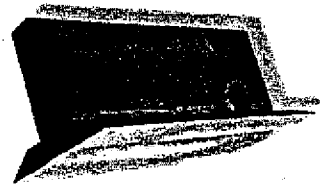
Figure 11b



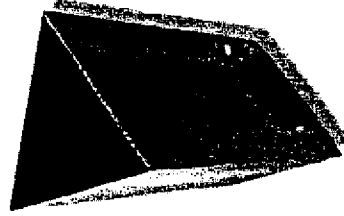
**Figure 12a**



**Figure 12b**



**Figure 12c**



## **EXHIBIT B**

# KONNEKER & SMITH

A Professional Corporation

## REGISTERED PATENT ATTORNEYS

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October 29, 2003

Scott Wendorf, Esq.  
Attorney – Intellectual Property  
Halliburton Energy Services  
P.O. Box 819052  
Dallas, TX 75381-9052

Re: Draft Patent Application  
Our File No.: HALB-2003IP009957U1USA  
Your File No.: 2003-IP-009957 U1 USA

Dear Scott:

Enclosed herewith is a copy in draft form, in both written and electronic media formats, of the above-identified patent application. As we discussed by telephone today, I will transmit the draft application to Mr. van Schoor of Mide Technology Corporation to coordinate review of the application by the inventors (listed on the first page of the application).

I will keep you advised of the progress of the application review. When the application is approved by the inventors, I will transmit appropriate Declarations and Assignments (assigning the invention to Halliburton) to Mr. van Schoor for execution by the inventors.

A related application (2003-IP-009957 U2 USA) having only Halliburton inventors is being mailed to you today, as well. The U2 application should be filed concurrently with this U1 application.

Very truly yours,

KONNEKER & SMITH, P.C.

Marlin R. Smith  
Enclosures